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The Effect of the Wave Form
# of the
Impressed Voltage
on the
Rotor Current
# of a
Three-Phase Wound-Rotor Induction Motor

by

ARTHUR BRUNO FOESTE

A Thesis Submitted for the Degree of

BACHELOR OF SCIENCE

Electrical Engineering Course

UNIVERSITY OF WISCONSIN

1917

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INTRODUCTION.

A search of the available technical literature and text books reveals the fact that very little experimental or analytical data are available concerning the shape of the electromotive force wave generated in the secondary of an induction motor. The only practical method of obtaining this wave-shape is by means of a search coil placed in the winding slots of the stator or rotor but under load conditions the inductive effect of the currents in the conductors distorts the voltage wave to such an extent that the true wave-shape would be more or less masked.

It is further noted that almost no determinations of the wave-shape of the current in the rotor have been made. In some cases a theoretical discussion has brought out the supposed wave-shape but the assumption of certain conditions and the failure to take into consideration other equally important conditions has given results which are of little value other than for the purpose of demonstrating certain fundamental theories.

The lack of knowledge concerning the action taking place in the rotor makes it rather difficult to predict the characteristics of an induction motor with any degree of accuracy and the control of certain factors, at present unknown or undetermined, may make it possible to improve greatly the operating characteristics of an induction motor. A complete understanding of these factors is essential to their control and to a definite knowledge of the actions taking place.

The results of any investigations along the lines indicated above should be of interest to designer and to those engaged in amplifying the theory of the induction motor.

GENERAL SURVEY.

The shape of the electromotive force wave at open circuit has been determined by Mr.C.F.Smith and the results have been published in The Mechanical Engineer of November 18, 1910. The data and curves were obtained by winding search coils in the stator slots and impressing normal voltage on the rotor while driving it at synchronous speed and speeds below synchronism. By this method the wave-form of the secondary electromotive force was obtained and the effects due to slots and teeth were separated from those due to distribution of the winding.

The wave of flux distribution is assumed to be the same as the electromotive force wave. In fact, while determining the wave-shape of the electromotive force, Mr.C.F.Smith has termed his discussion "Irregularities in the Rotating Field of a Polphase Induction Motor". The assumption of similarity of electromotive force wave and flux wave does not take into account the effect of the impedance drop in the winding when the circuit is closed and the assumption is therefore erroneous.

The only available data on the wave-shape of the current was an article by Mr.H.Weichsel on "Wave Shape of Currents in an Individual Rotor Conductor of a Single-Phase Induction Motor". Apparently no work has been done with polyphase motors and the characteristics of the current in the rotor winding of the polyphase motor are therefore not very well known.

Since only very meager data concerning the three important actions in the induction motor rotor are available it is impossible to determine,with any degree of accuracy, the relations existing between secondary electromotive force, flux, and secondary current. The entire action taking place in the

rotor when an induction motor operates is therefore very little understood and not considered to any great extent in the design of the motor except insofar as certain conditions of design must be fulfilled. Neither is the effect of the primary winding on the secondary reactions very well understood.

PURPOSE OF THIS THESIS.

The purpose of this thesis is to determine the effect of the wave-form of the impressed voltage on the rotor current of three-phase induction motors.

It is intended to show, by means of a number of different voltage waves impressed on the primary of an induction motor, what effect the presence of higher harmonics in the voltage wave has on the wave-shape of the rotor currents and to separate, as far as possible, the effects of harmonics from those of slots, teeth, and the distribution of the windings.

THEORY OF THE INDUCTION MOTOR.

When a three-phase voltage is impressed on the stator of a three-phase induction motor a flux is generated by the currents set up in the windings. This flux can easily be proven to be constant in value and it rotates at a uniform angular velocity. Suppose that the rotor is revolving at synchronism; that is, if the angular velocity of the rotating flux is 1200 revolutions per minute the rotor is to revolve at 1200 revolutions per minute also. Then, with respect to the stator flux the rotor bars are not moving and cut no flux. Therefore, no electromotive force is induced in the rotor conductors and there can be no flow of current.

When the rotor revolves, however, there are rotational losses even at no-load and these losses must be overcome by currents in the rotor. When the motor operates at no-load the difference between the speed of the rotor and synchronous speed is just sufficient to produce that current and the difference between the synchronous speed and the actual speed is known as the slip. The slip causes motion of the rotor conductors relative to the stator flux and this cutting of the flux induces electromotive forces in the rotor which produce the currents needed. The difference between the speeds of the flux and the rotor conductors will be just sufficient to cause enough current to flow in the rotor to produce the torque required to overcome the rotational losses.

When the motor is loaded a larger torque and therefore a greater current is demanded. To obtain a larger current a greater electromotive force is necessary and this increase in

the electromotive force is caused by the increase in the slip. In other words, the condition of equilibrium is reached when the difference is speeds of the magnetic field and of the rotor will be just sufficient to cause enough current to flow in the rotor to produce the torque demanded for the load and to overcome the rotational losses.

In making the calculations for the design and performance of an induction motor it is always assumed that a sine wave of voltage is impressed on the stator and that the flux has a sine distribution. Actually neither one of these conditions is even approximately true and the calculations should be based on the principle of the equivalent sine waves being substituted for the actual waves.

In ordinary commercial alternators, the wave form of the voltage is usually very good for practical purposes but it is not a sine wave for the expense connected with obtaining even approximately a sine wave of voltage would be very great. We thus reach the first error in our assumptions at the outset of the calculations.

Our second error is brought into the calculations when we start with a certain magnetizing current and from this deduce the field form and the electromotive force wave-form. To be exact, we should obtain the field form from the electromotive force wave-form and from this obtain the form of the magnetizing current. Attacking the problem from this angle we should find that, due to the saturation of the iron, a third harmonic of greater or less amplitude is introduced. Further, there will be numerous harmonics introduced to suit the particular winding in the stator slots.

The limitations of the stator winding introduce what Dr.S.P.Smith has been pleased to call the "spacing ripple". If it were possible to distribute the stator winding uniformly over the face of the armature a sine wave of flux distribution could be obtained. However, the winding must be laid in slots and there is thus a non-uniform increase of the flux from the edge to the center of the pole. The form of the flux wave as plotted from a consideration of the ampere turns per slot is given in Fig.1. The maximum flux marks the center of the pole.

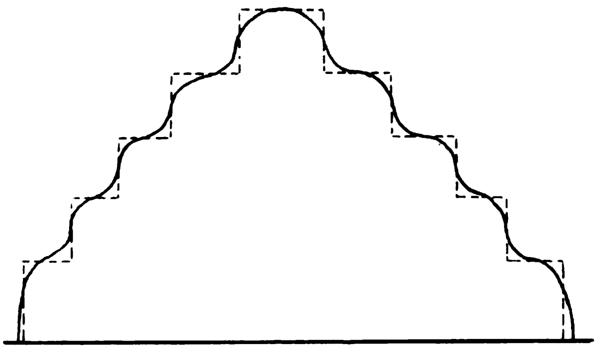


Fig. 1.

As the armature revolves the teeth pass under the pole of the motor and produce pulsations of the flux of two kinds; (1) a pulsation due to the change in reluctance under the pole and (2) a swinging of the flux along the periphery of the rotor as a tooth under the horn of the pole is replaced by a slot. The first of these pulsations is due to the fact that the reluctance varies as the number of teeth under the pole changes from one value to another and back again as the rotor revolves. This first increases and then decreases and then increases again the value of the flux and causes ripples in the flux wave. The second of these pulsations is due to the flux sweeping across the face of the armature. As a tooth is replaced by a slot at the horn of the pole the reluctance of the magnetic path increases at this point and the flux attempts to follow the tooth toward the center of the pole. When at the next instant the slot has been replaced by another tooth the reluctance at the horn has

again been decreased and the flux swings back to this point. this swinging of the flux causes pulsation in the electormotive force wave induced in the rotor. Messrs. Smith and Boulding employ the term "tooth ripples" for this pulsation to distinguish them from the "spacing ripples" previously explained.

The higher harmonics of the impressed voltage, the spacing ripples, and the tooth ripples all have an effect on the wave-shape of the induced voltage. The result is an induced wave which is extremely complicated in form and which has harmonics of a high order in its fabrication. The wave-shape of the rotor current will for the most part approximate the shape of the electromotive force wave because an induction motor is equivalent to a transformer with a non-inductive load and therefore a determination of the wave-shape of the rotor current will indicate approximately what the wave-shape of the rotor voltage will be.

The shape of the current wave may be obtained by means of a search coil or by means of a shunt in the rotor circuit. In the search coil method a coil of fine wire is placed in slots with the main winding and is influenced by the same field which effects the main rotor conductors. The taps to the search coils are brought out to slip rings and connection is made with the oscillograph at this point. The search coil method is applicable especially to the squirrel-cage induction motor.

The shunt method makes use of a shunt in the short-circuited rotor circuit and the current flowing through this shunt is taken to the oscillograph vibrators. This method is in common use in most cases when currents of more than one-half ampere are present.

DESCRIPTION OF METHOD AND APPARATUS.

The induction motors used for these experiments were those in constant use in the Electrical Engineering laboratory. The machines are of standard make such as are in commercial use at the present time.

The impressed voltage was obtained from three different sources in the laboratory in order to obtain the different wave-shapes required. Two of the three alternators used were small General Electric Co. three-phase, 60-cycle, 110-volt alternators and were driven by electric motors. The third machine was an Allis-Chalmers three-phase, 60-cycle, 110-volt alternator used as the ordinary source of three-phase supply in the electrical laboratory. Reference to the oscillograms shows that both the General Electric alternators have very good wave-forms but the Allis Chalmers alternator has a flat-topped wave which is as much distorted as the voltage wave of commercial alternators would ever be.

The induction motors were loaded by belting them to a direct current generator and connecting an incandescent-lamp load to the generator. By this means a steady load was obtained on the induction motor and the pulsations due to fluctuating load were eliminated. At start the induction motor, unloaded, was connected directly across the line. This was possible because the voltage disturbances in the line at start were unimportant and because all of the induction motors were of small size. The voltage, current, and frequency were read at the motor by means of a three-phase board.

It was found unnecessary to adjust the Allis Chalmers alternator after the voltage had been set at the desired value

by means of the alternator field rheostat. The steam engine used for driving automatically kept the frequency constant and the alternator was of sufficient size to supply the necessary current with out an appreciable voltage drop.

The General Electric alternators were driven by direct current motors and the speed was kept constant by means of a motor field rheostat. In order to compensate for the voltage drop under load the alternator field excitation was increased under load. All control apparatus was placed at the induction motor in order to expedite the governing of the conditions of the test.

The wave-shape of the rotor current was obtained by the shunt method. The rotor slip rings were short-circuited externally through an exposed shunt-bar and the desired amount of current was passed through the oscillograph by connecting the taps of the oscillograph to the shunt-bar. The diagram of connections indicates clearly the method of obtaining the desired current for the oscillograph.

The shunt method of obtaining the wave-form of the rotor current was used because of the error introduced by the search coil and because of construction difficulties. A search coil wound in the rotor slots with the main conductors is subject to inductive action because of the current in the main conductors. This is likely to cause a distortion of the actual wave of rotor current because the search coil is subjected not only to the main field of the alternator but also to the field caused by the currents in the main rotor conductors.

Some of the difficulties encountered bear mentioning to illustrate the methods used in overcoming them. It was

necessary, in order to obtain a curve of the rotor current which could be studied intelligently, to use a current vibrator which was about four times as sensitive as those ordinarily used in the oscillograph. By this means the higher harmonics were adequately shown.

The most prolific source of error in making the tests was at the contact point between the brushes and the slip rings. Some of the oscillograms show a sudden decrease in amplitude and then an increase. This is undoubtedly due to poor contact between brushes and slip rings and was overcome to some extent by making the contacts as good as possible.

One of the first things noticed in making the tests was that the rotor current wave was not stationary on the tracing table. This led to the supposition that the same thing might occur in the exposure of the film but no evidence of a non-stationary wave was discovered. Mr.H.Weichsel (Proceedings of the American Institute of Electrical Engineers June 1911) explains this phenomenon by resolving the total current into two different waves, one of which has "line plus speed" frequency and the other having slip frequency. The curves he gives show clearly that is is impossible to produce a stationary rotor current wave on the tracing table with the standard design of oscillograph because the wave repeats itself only after a comparatively long period of time.

OPERATIONS.

The method of obtaining the oscillograms was as follows: The induction motor under test was connected to the source of power supply and was belted to a direct current generator to obtain the required loading. The motor was then operated under load until it had heated about to the ordinary running temperature.

The voltage and frequency were then adjusted to their normal values and the motor load adjusted until the alternating current ammeter indicated the full current input. The oscillograph was then connected into the oscillograph circuit (see diagram of connections) and the amplitude of the rotor current wave adjusted to the desired value by increasing the voltage drop over the shunt path. A wave of line current was also obtained by a connection similar to that employed for the rotor current wave-form. The wave-form of the impressed voltage was also obtained by connecting one of the vibrators across the supply line in series with an alternating current voltmeter. The impressed voltage wave-form was obtained for purposes of identification and for the purpose of studying the wave-shapes.

The oscillograph motor was then started and the arc was lighted. The three waves could then be seen on the tracing table and they were adjusted as to amplitude and position on the film. The film in its holder was attached to the oscillograph after the shutter had been closed. The direct current motor for driving the film drum was then started and the speed of the drum adjusted. By an electrical contact the shutter was then opened and the film exposed for one complete revolution of the drum.

In this manner the wave-shape of the rotor current was obtained under full load and under no-load. Similarly, with two other voltage waves the full load and no-load rotor current wave-shapes were obtained.

Another induction motor was then used and the three wave-shapes previously employed were again used to obtain the effect of a particular wave-shape of impressed voltage on the rotor current of that induction motor. By these methods three different induction motors were operated, each on three different wave-shapes of line voltage, at full load and at no-load.

CONCLUSIONS.

Comparing Records Nos. 1, 3, and 5 we find that No. 1 shows the most irregular secondary current curve. No. 5 also has a more irregular secondary current wave than No. 3. In each case we see in the primary current wave a variation in the amplitude of the wave. The primary wave reaches its maximum when the secondary current is zero and reaches its minimum when the secondary current is a maximum. This would seem to indicate that the secondary current influences the primary by inductive action and causes pulsations in the primary current.

A comparison of Records Nos. 2, 4, and 6 indicates that the higher harmonics have the greatest amplitude in Record No. 2 and the harmonics of Record No. 4 are of less amplitude than those of Record No. 6. Reference to the voltage curves shows that the voltage applied on Record No. 4 is more nearly a sine wave than that of Record No. 6 which, in turn, is more nearly a sine-wave than that of Record No. 2. The primary current wave in Record No. 2 shows a comparatively large higher harmonic while the primary current wave of Record No. 4 seems to be almost a sine wave, having only spacing ripples and tooth ripples in evidence.

Records Nos. 7, 9, and 11 show the same general characteristics as Records Nos. 1, 3, and 5. Again the irregular voltage wave induces larger higher harmonics than the approximate sine wave of voltage. In Records Nos. 7, 9, and 11 the pulsations of the primary current are not in evidence.

Records Nos. 8, 10, and 12 show the same characteristics as Records Nos. 2, 4, and 6.

Records Nos. 13, 15, and 17 show the same general characteristics as Records Nos. 1, 3, and 5.

Records Nos. 14, 16, and 18 show the same general characteristics as Records Nos. 2, 4, and 6.

The above observations indicate that at full load and at no-load the more irregular the wave-form of the impressed voltage the greater will be the amplitude of the higher harmonics of the secondary current wave. The harmonics in the secondary current wave are for the main part due to spacing ripples and tooth ripples and would probably be present even if a pure sine wave of voltage were impressed on the stator. These ripples are, however, amplified by the higher harmonics of the impressed voltage wave.

A comparison of the effects of one wave-form on three different machines indicates mainly that the harmonics are due almost entirely to the distribution of the windings and to the slots and teeth. The only method by which a comparison could be made on this basis is by the separation of the harmonics due to the impressed voltage.from those due to the characteristics of the machine. This was not possible with the limited time and apparatus at hand.

The probable reason for the exaggerated harmonics in the secondary current curve is that an induction motor resembles a condenser. This is due to the fact that while the slip is small in relation to the flux due to the fundamental it is, however, large in relation to the fields of the higher harmonics which rotate at a speed which is some multiple of the main field. Therefore the harmonics in the wave of impressed voltage will

induce in the rotor voltages which have a comparatively large value. These voltages will produce in the rotor and therefore in the stator, currents of large amplitude.

These higher harmonics in the rotor current not only contribute nothing to the torque of the motor but they also increase the heating in the motor and reduce its rating. This, however, is not very serious as under load, it will be observed, the higher harmonics are only a small percent of the total rotor wave and their effect is not of as great importance as would first be imagined. If, therefore, the manufacturing expense must be materially increased to reduce these harmonics to their minimum value it is not economical to refine the construction to such a degree. Rather it is better to reduce the rating of the motor slightly if this proves necessary.

One feature of interest in connection with these higher harmonics relates to the question of wound rotors versus squirrel-cage rotors. If a single coil is directly short circuited on itself, as would practically be the case in the squirrel-cage rotor, we should probably obtain a considerable current of high frequency. But by connecting in series the conductors in several slots we find that the resultant voltage due to irregularities of the field is much decreased and, at the same time, the impedance of the circuit in which this voltage acts is materially increased. The high-frequency, pulsating currents may therefore be reduced to a relatively small value in a wound rotor and its rating may probably be increased.

BIBLIOGRAPHY

Specifications and Design of Dynamo-Electric Machinery.

by Miles Walker.

Proceedings of the American Institute of Electrical Engineers

June 1911. Wave Shape of Currents by H. Weichsel.

General Electric Review. March 1916.

Higher Harmonics of Induction Motors.

Electrician (London) December 11, 1914.

Magnetic Field of the Three-Phase Induction Motor.

Mechanical Engineer November 18, 1910.

Irregularities of the Field of an Induction Motor.

Electrical Engineer (London) January 28, 1910.

Relation Between Stator and Rotor Circuits.

Electrical World July 28, 1910

Space Distribution of Magnetomotive Force.

APPENDIX.

IDENTIFICATION DATA.

Motor #A is a three-phase induction motor. It is a 110-volt, 6-pole, 60-cycle machine at is rated at 5 H.P. at 1200 r.p.m. It is numbered E.E.1041.

Motor #B is a three-phase induction motor. It is a 110-volt, 6-pole, 60-cycle machine and is rated at 5 H.P. at 1200 r.p.m. It is numbered E.E. 1391.

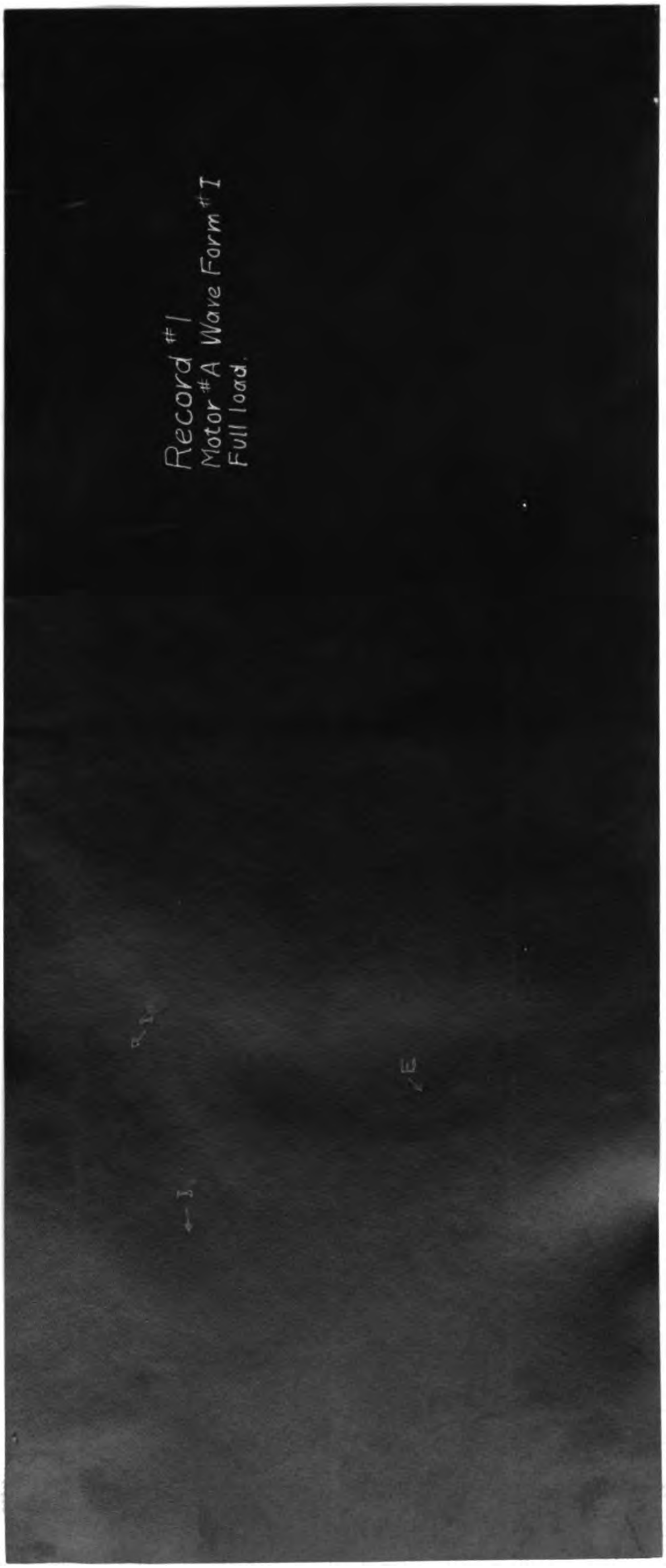
Motor #C is a three-phase induction motor. It is a 110-volt, 4-pole, 60-cycle machine and is rated at 5 H.P. at 1800 r.p.m. It is numbered E.E. 1042.

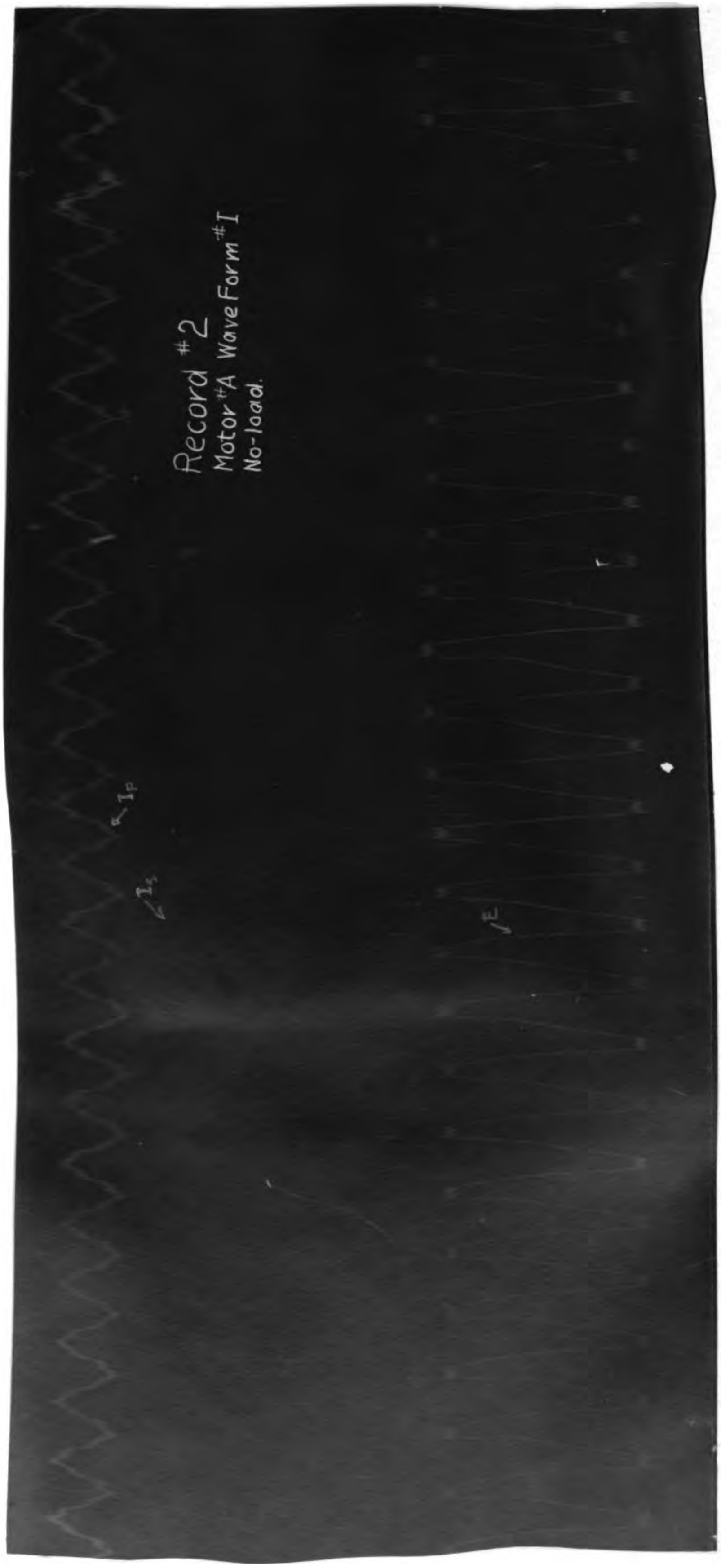
Wave-Form #I was taken form an Allis Chalmers alternator. This alternotor supplies three-phase power at 110 volts and 60 cycles. It is numbered E.E. 1015.

Wave-Form #II was taken from a General Electric alternator. This alternator supplies three-phase power at 110 volts and 60 cycles. It is numbered E.E. 1029.

Wave-Form #III was taken from a General Electric alternator. This alternator supplies three-phase power at 110 volts and 60 cycles. It is numbered E.E. 1292.

The oscillograms showing the wave-form fo the voltage of the three alternators are given on pages XX, XXI, and XXII.


Record #I
Motor #A Wave Form #I
Full load.
I
E
I



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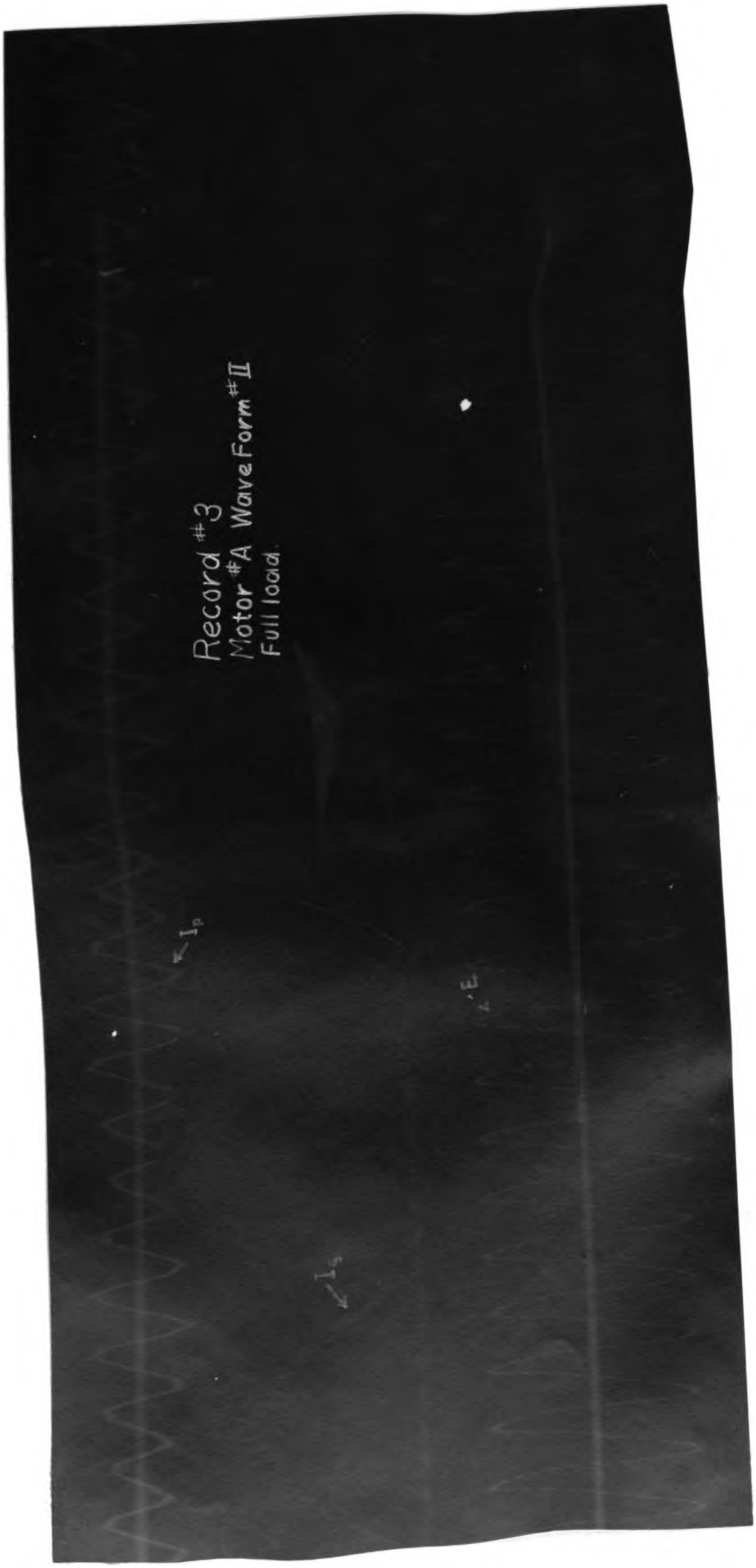
No-load.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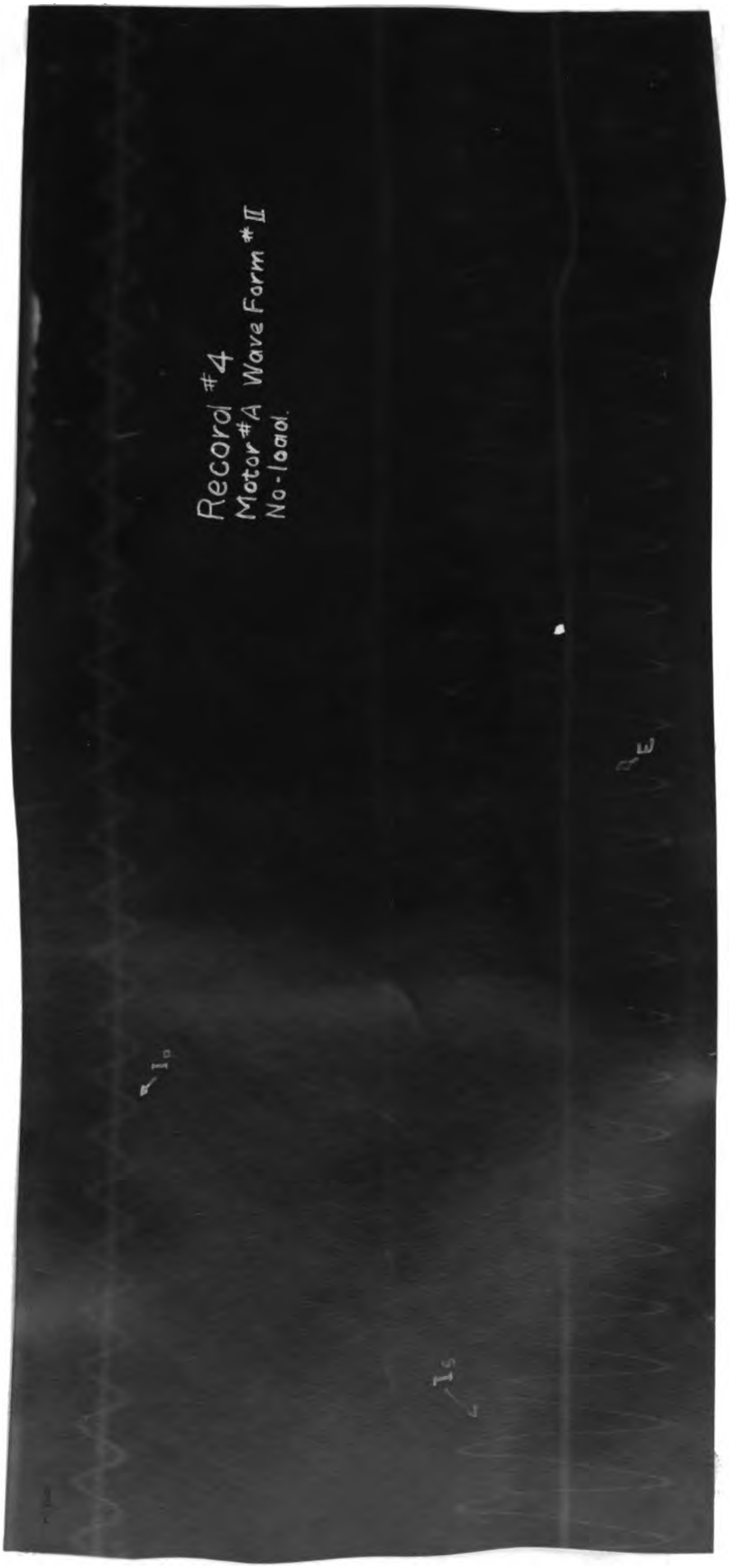
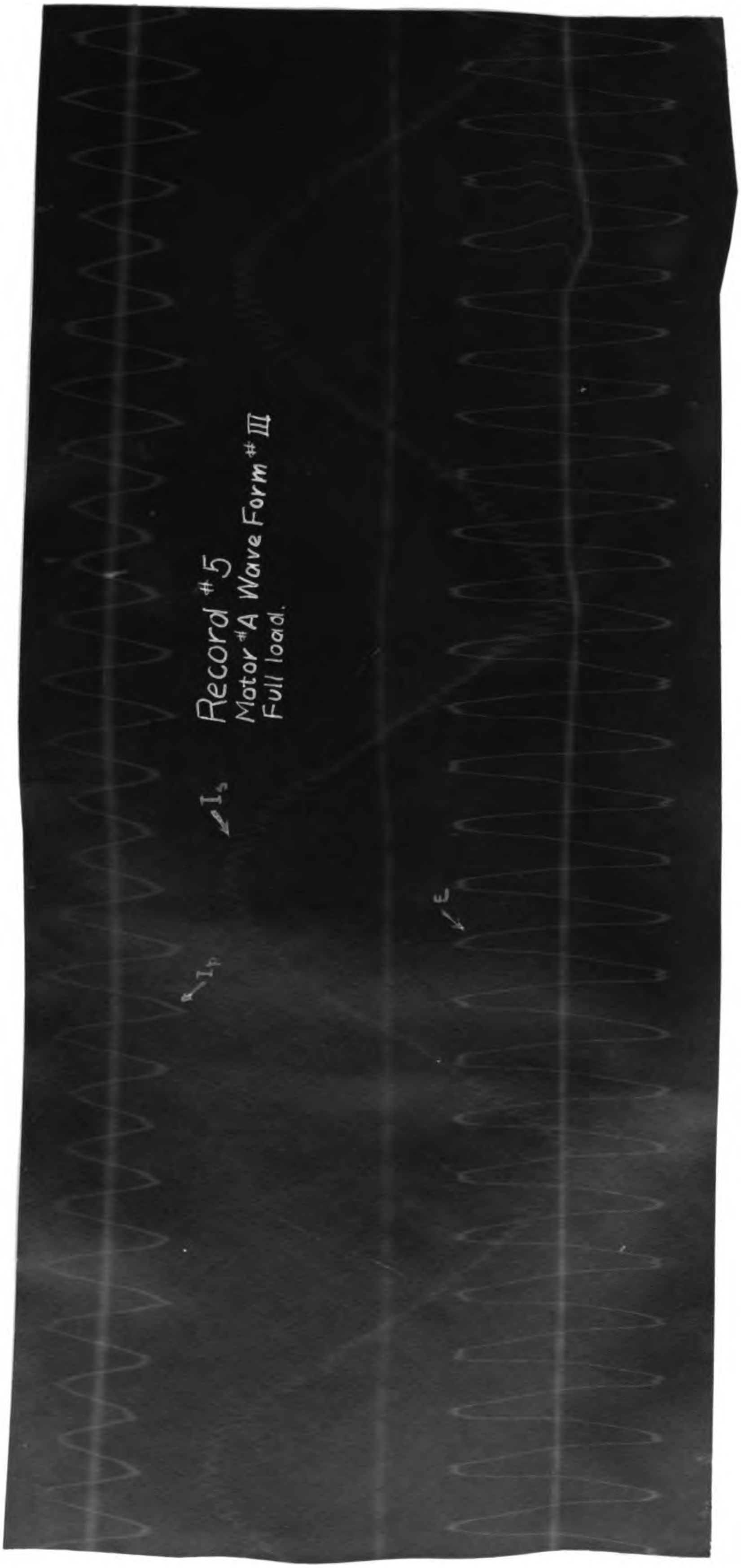
V

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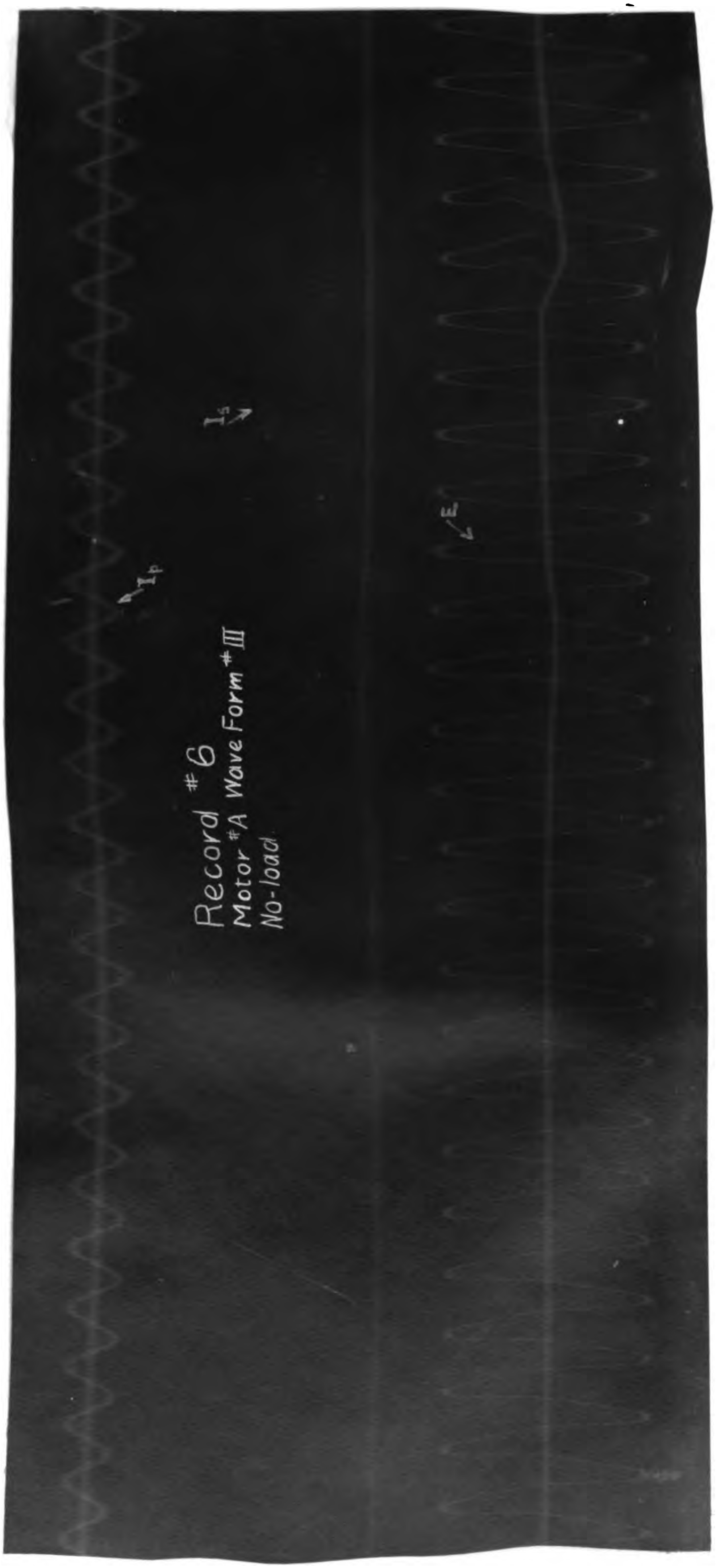
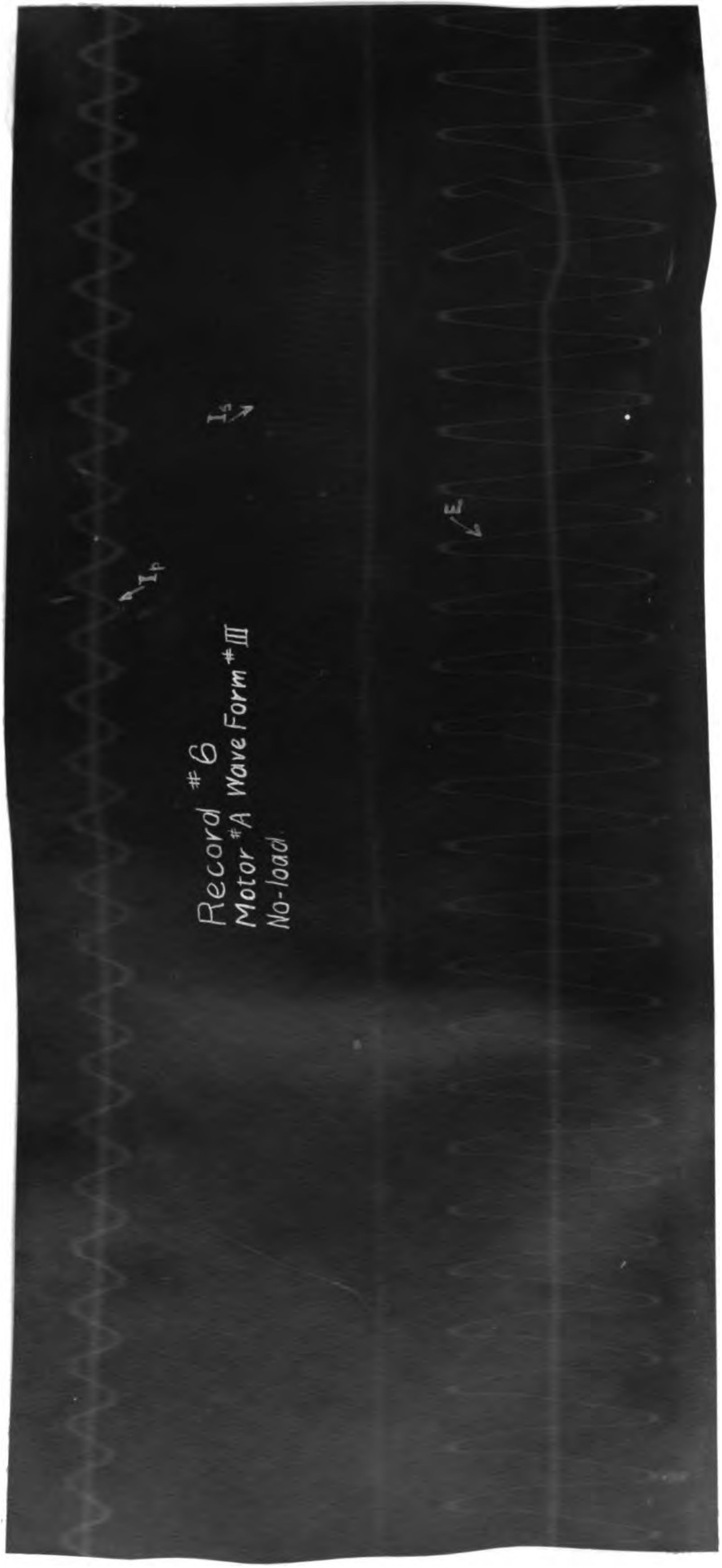
I_s
E
I_p


Record #6
Motor #A Wave Form #III
No-load
I_p
I_s
E


Is
E
Ip
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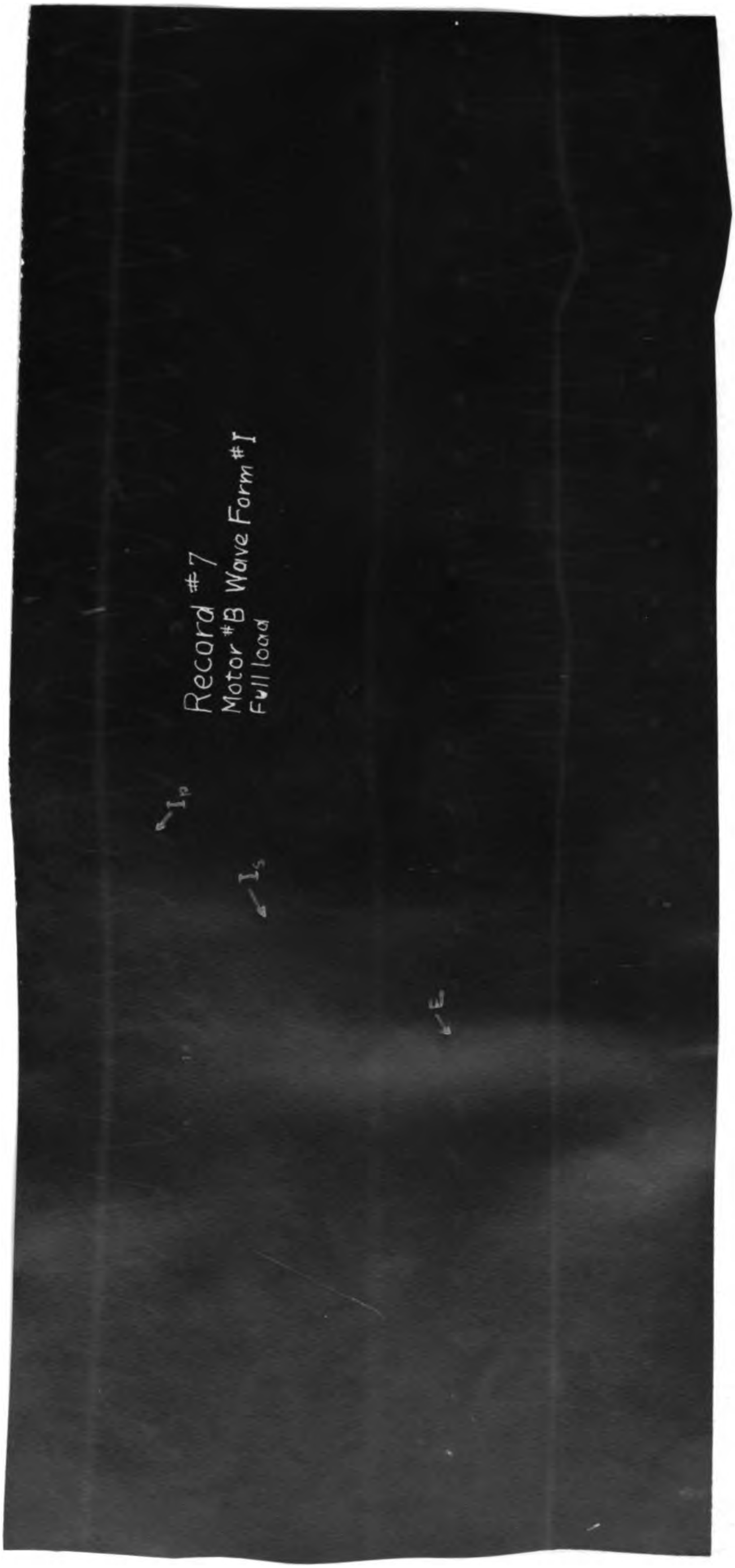
No-load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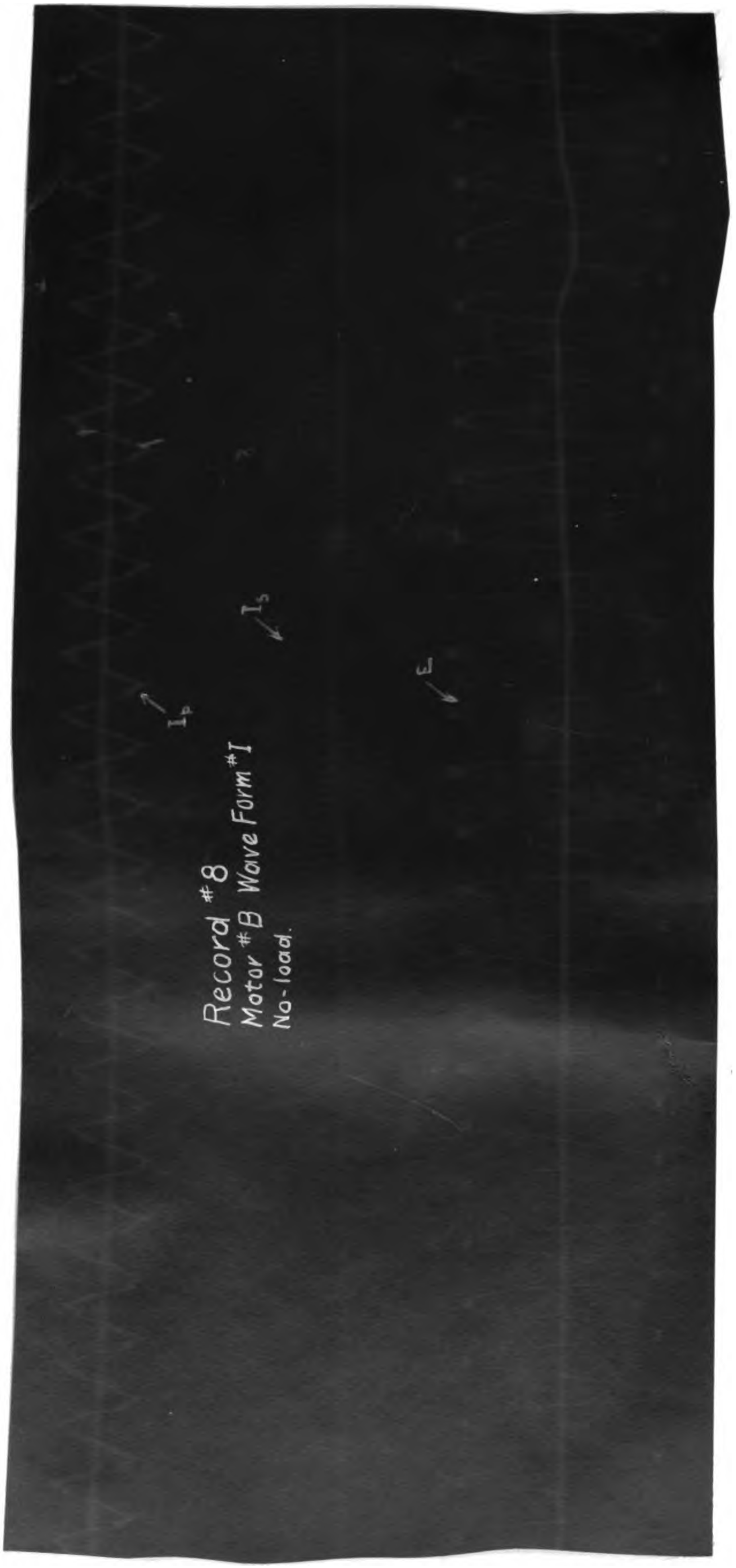
Motor #B Wave Form #I
Full load
I_p
I_s
E


I_p
I_s
E
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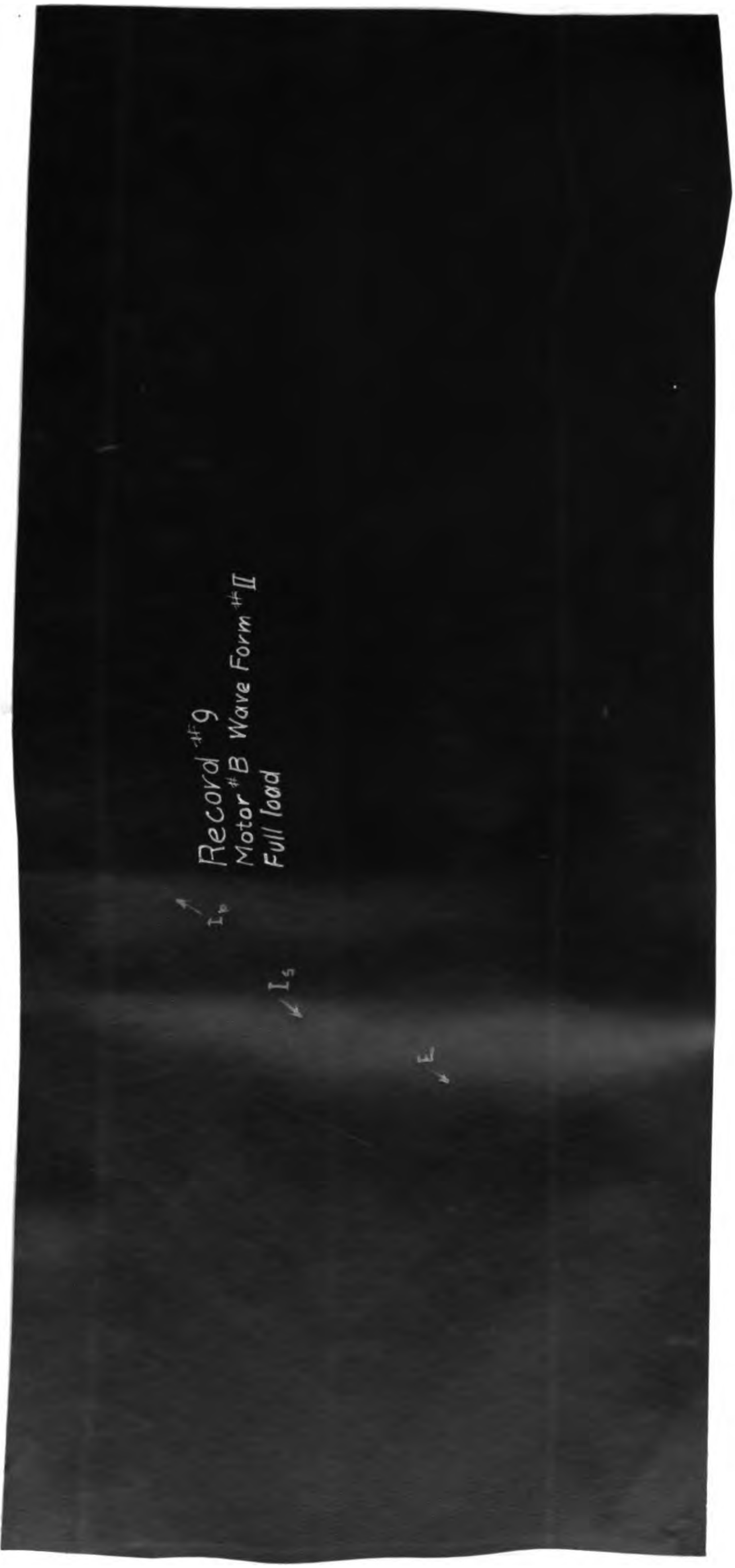
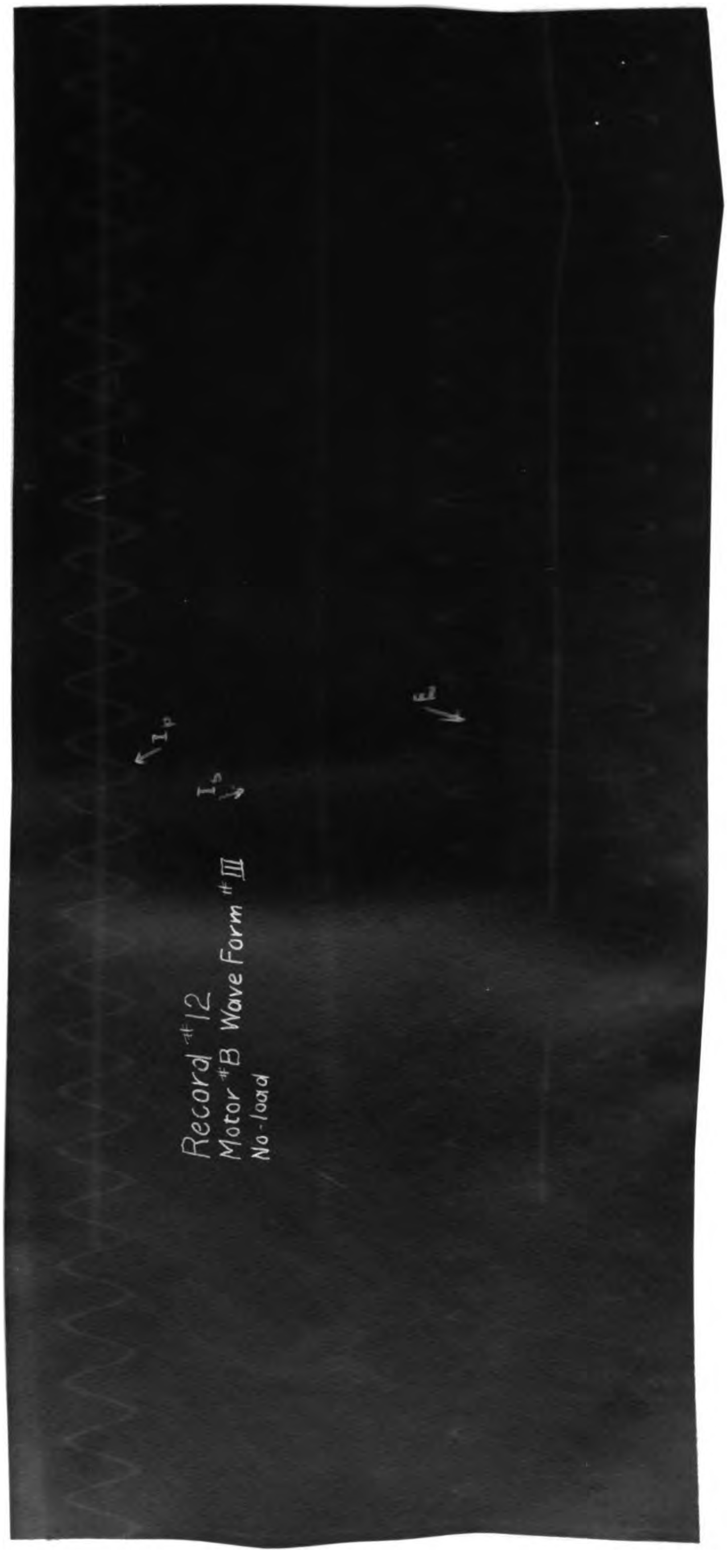
No-load.

X



Record # 10
Motor # B Wave Form # II
No-load.
I_p
I_s
E

Record #11
Motor #B Wave Form #III
Full load.
I_p
I_s
E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E
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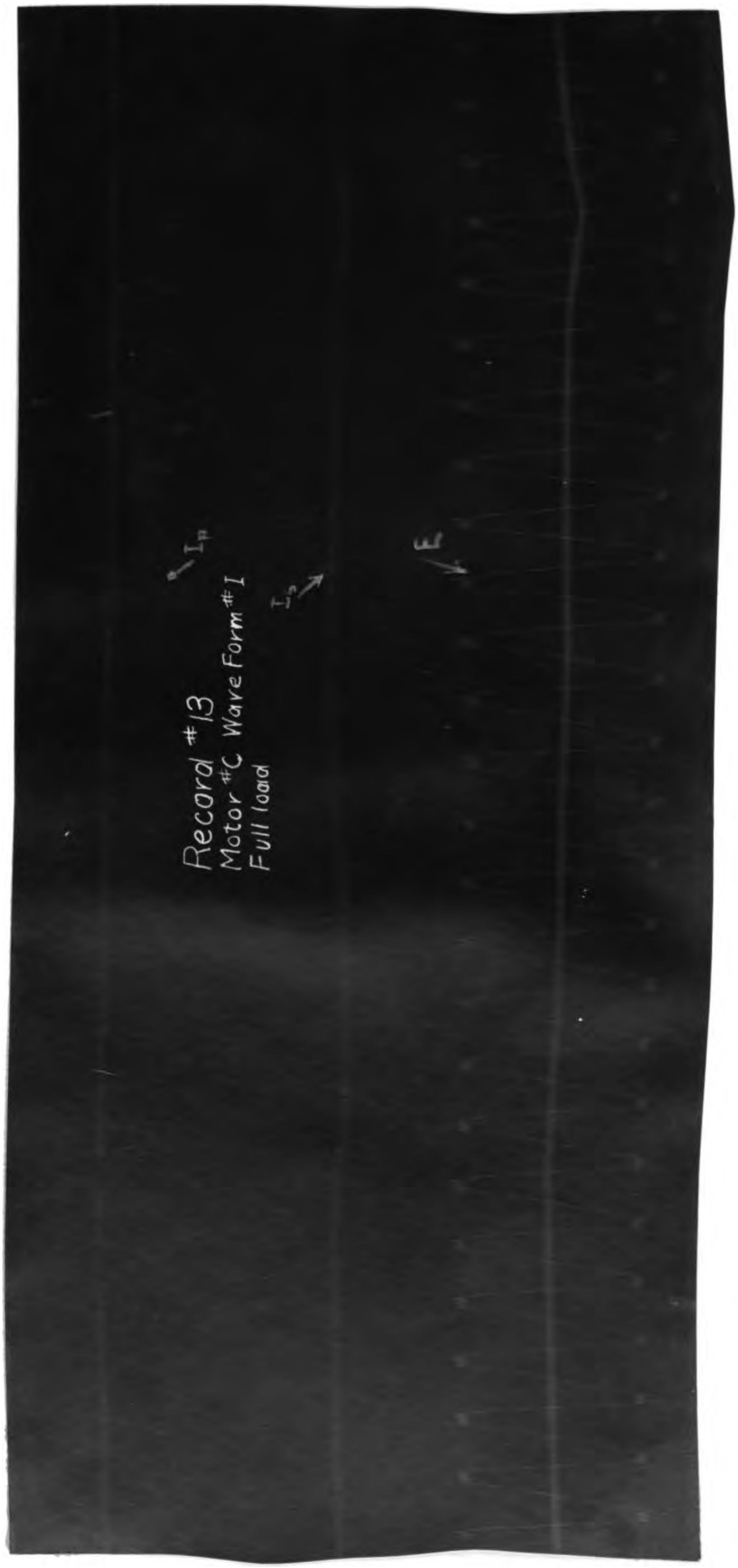
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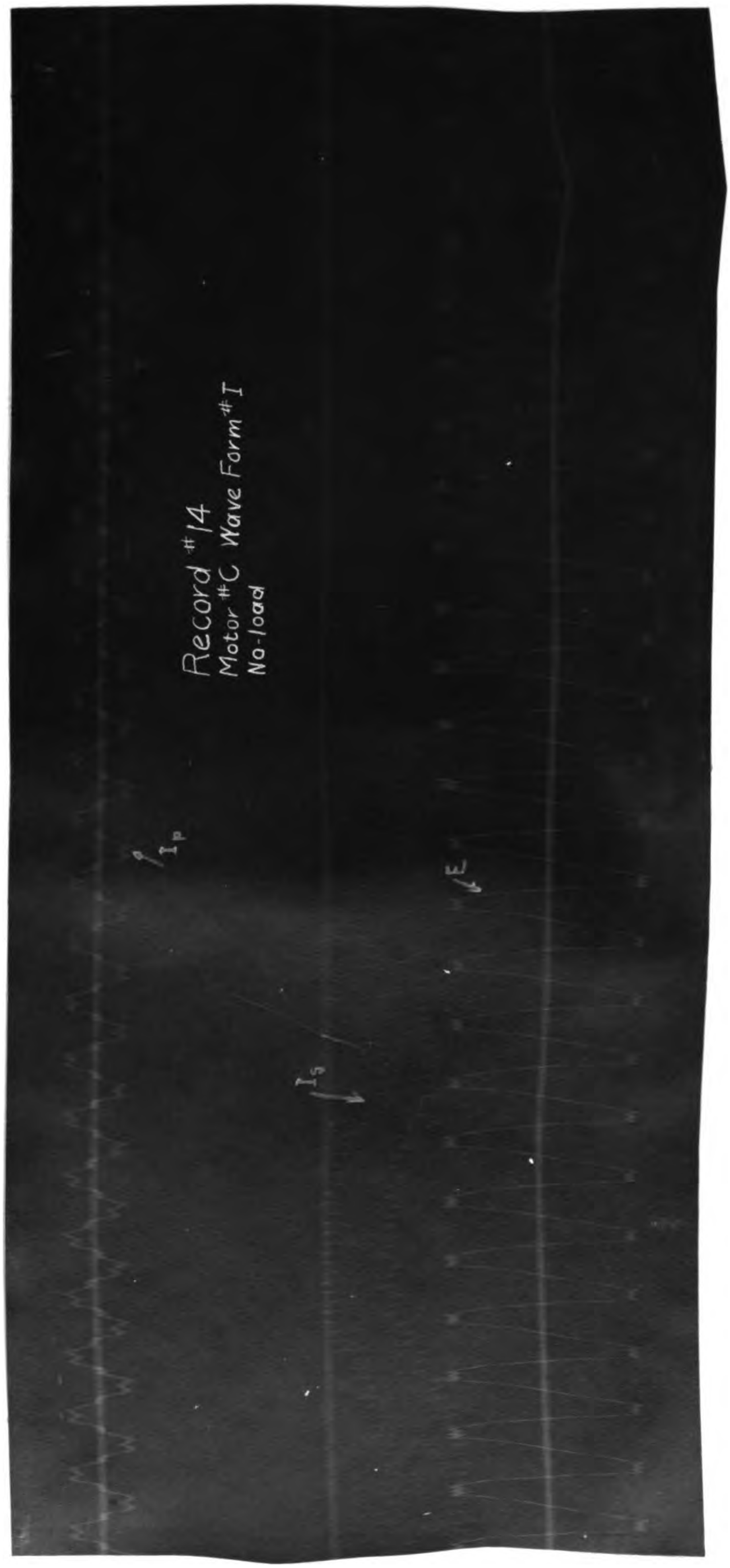
Motor #C Wave Form #1
Full load
I_p
I_s
E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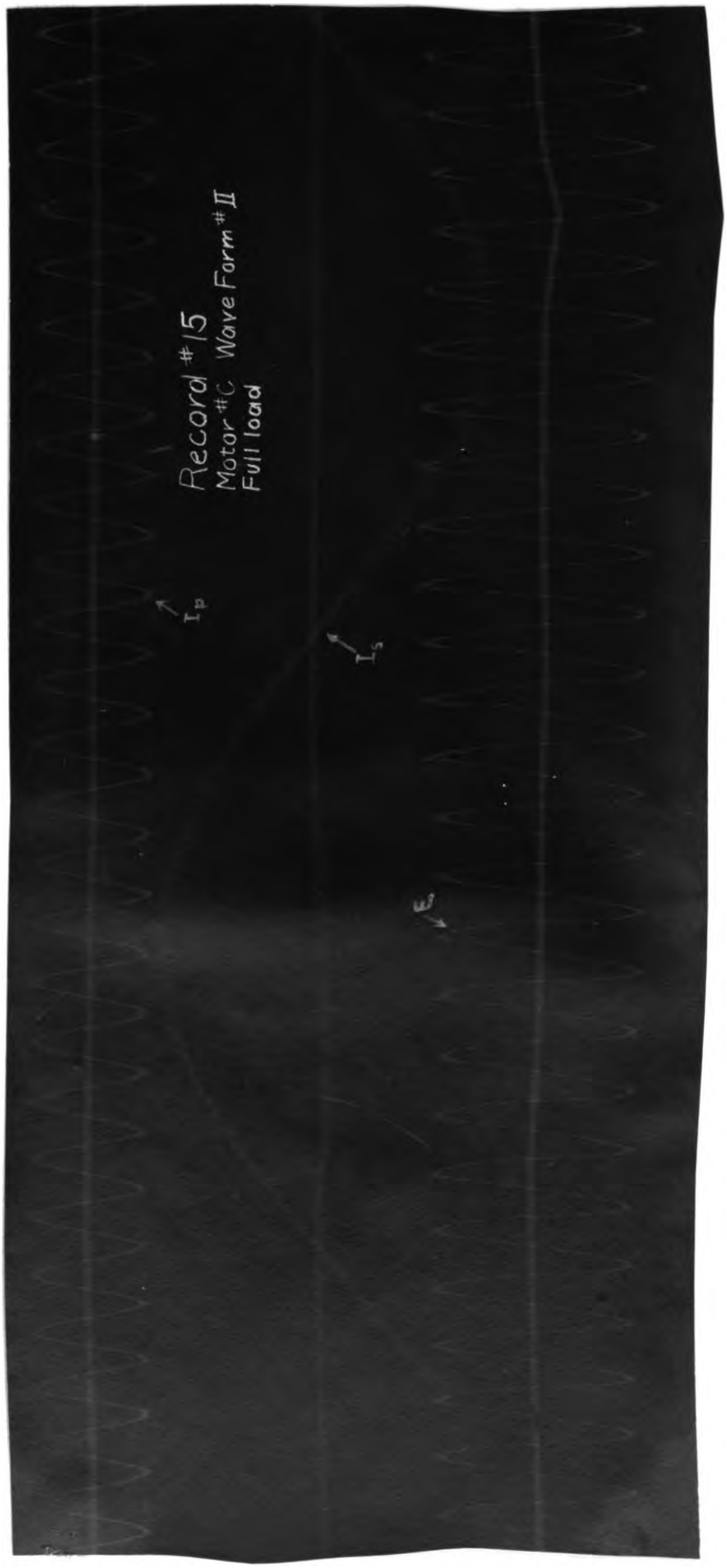
I_s
E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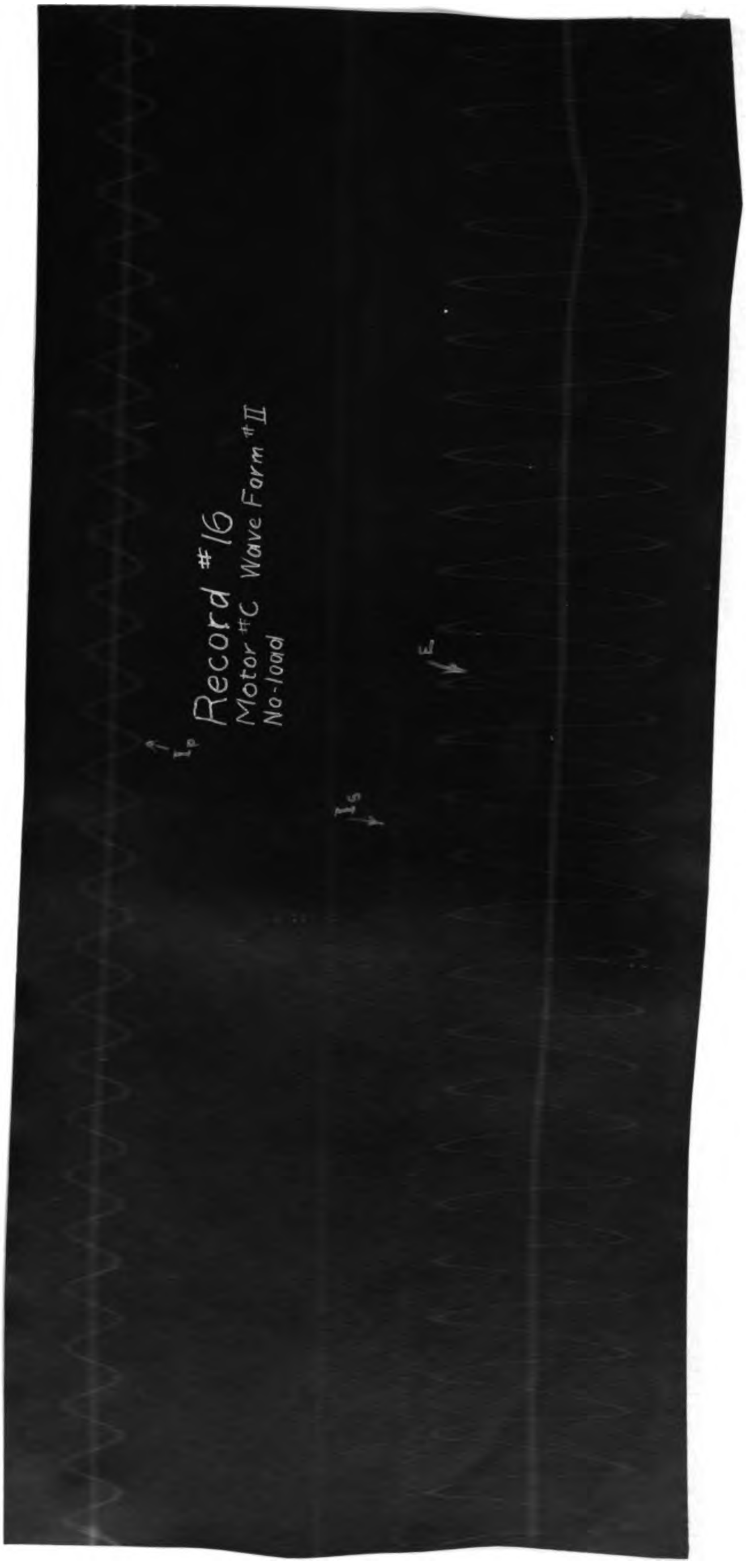
I_s
E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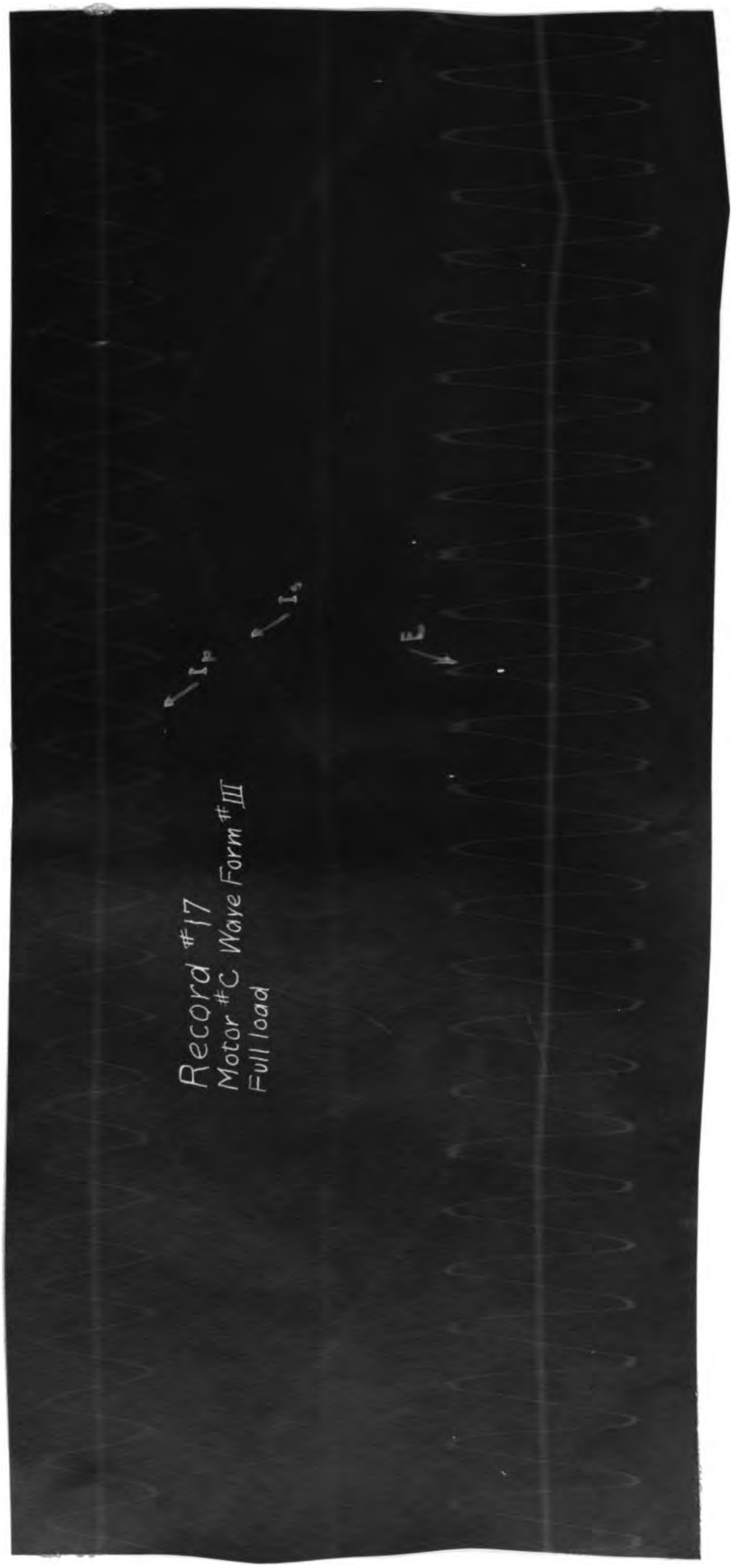
No-load
Ip
Is
E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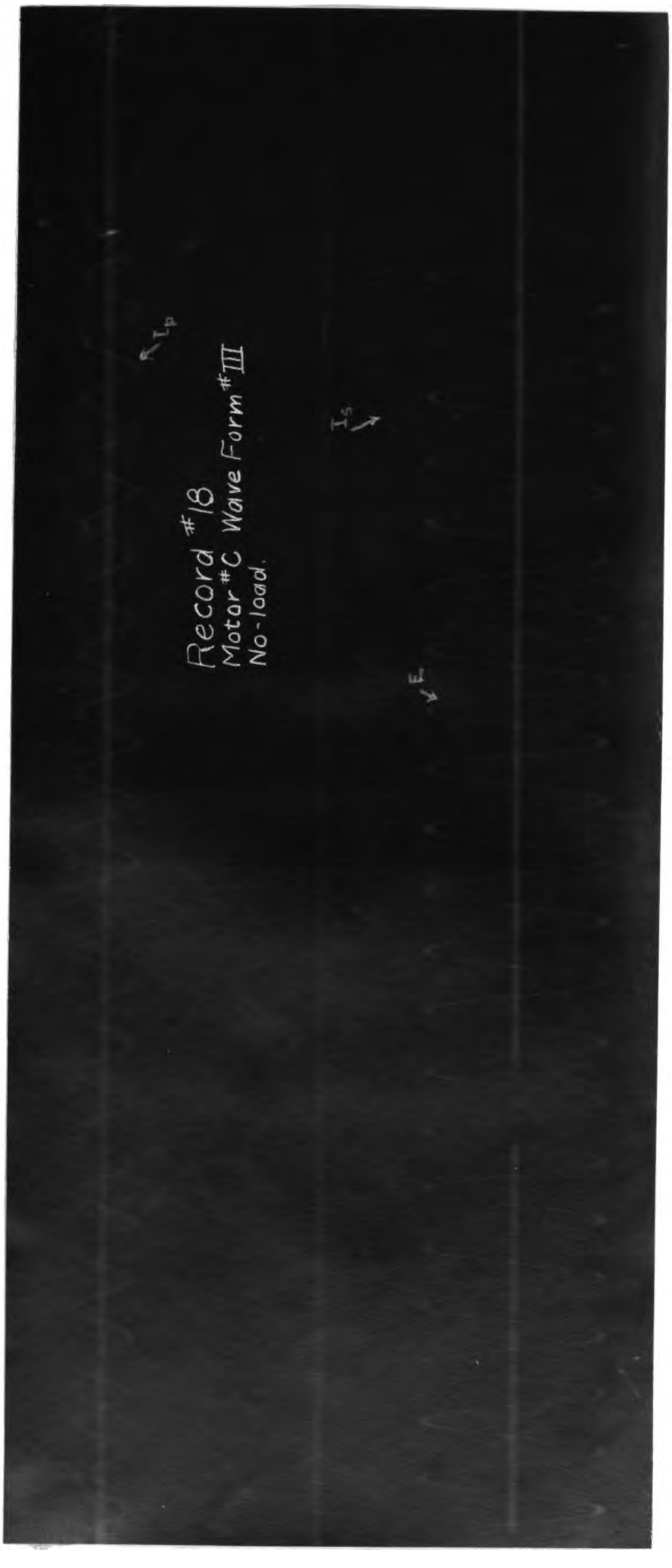
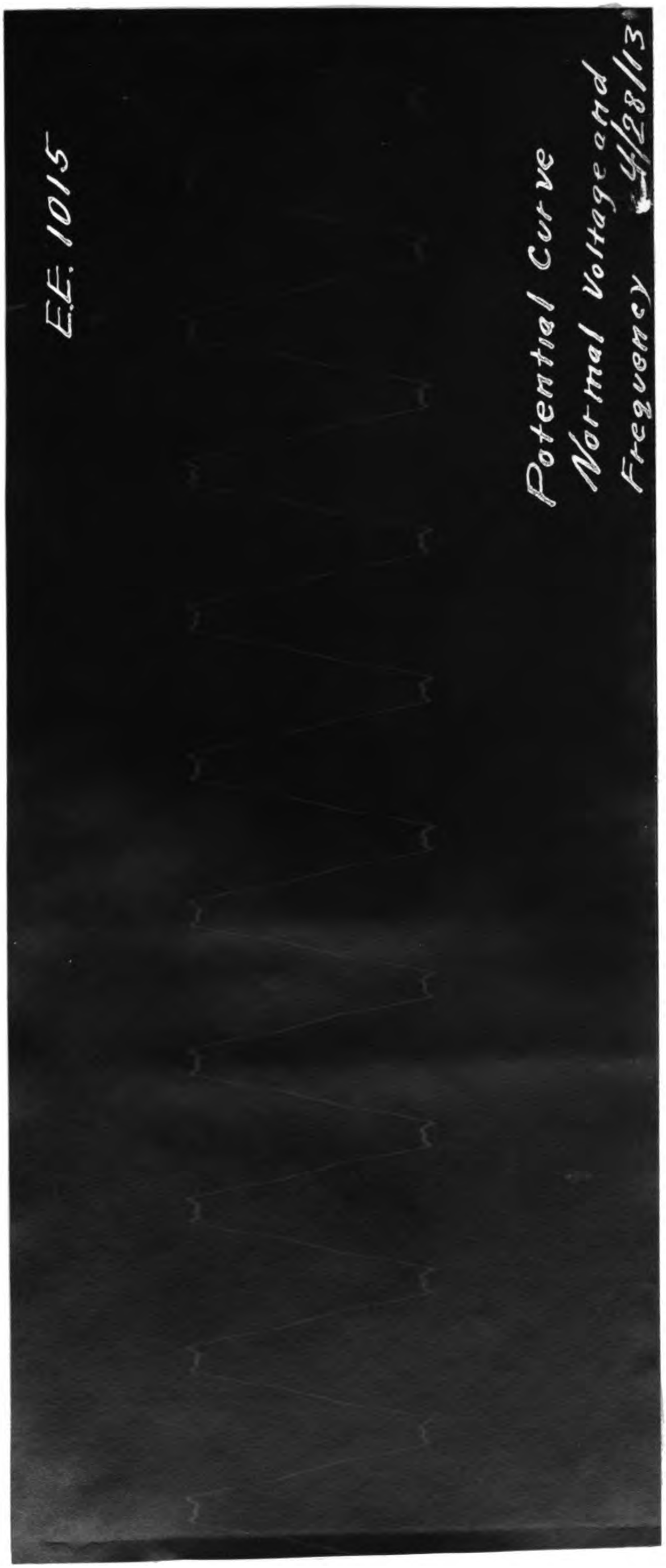
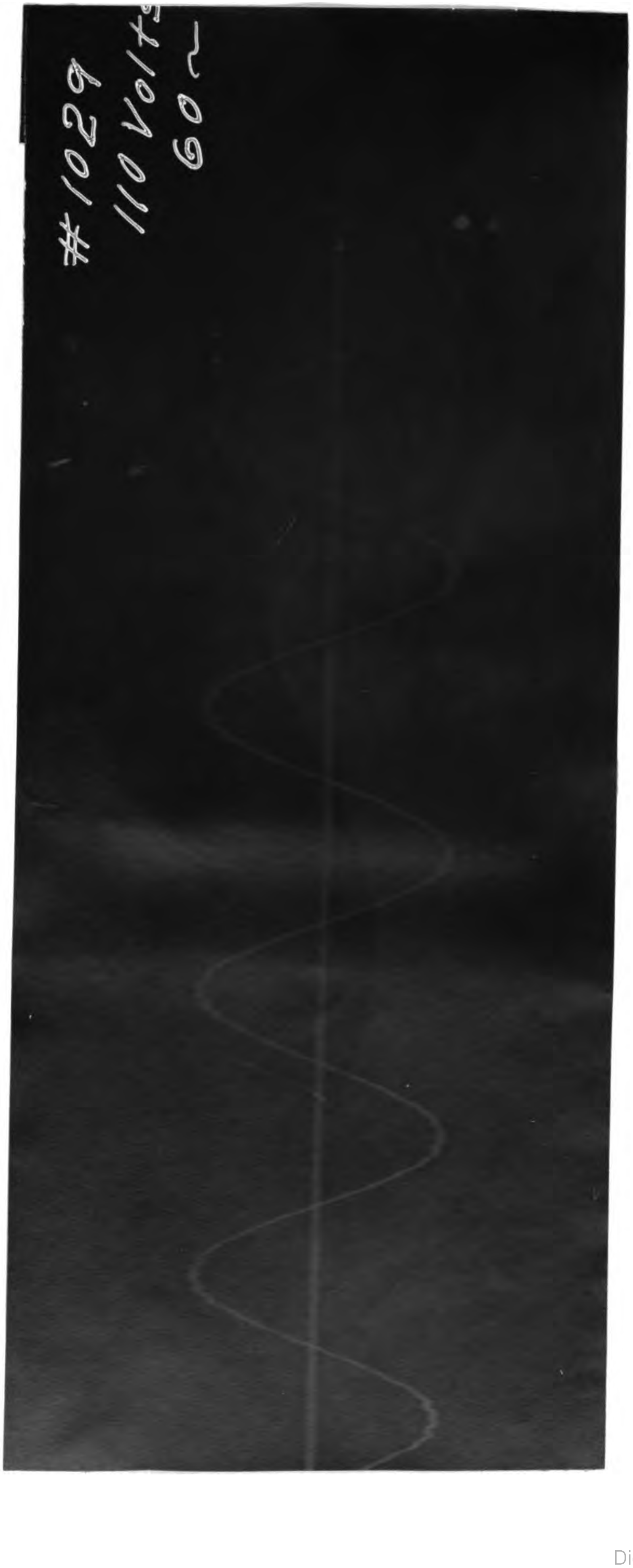
Motor #C Wave Form #III
Full load
I_p
I_s
E


Record #18
Motor #C Wave Form #III
No-load.
I_p
I_s
E



E.E. 1015

Potential Curve
Normal Voltage and
Frequency 4/28/13


#1029
110 Volts
60~

XXII.

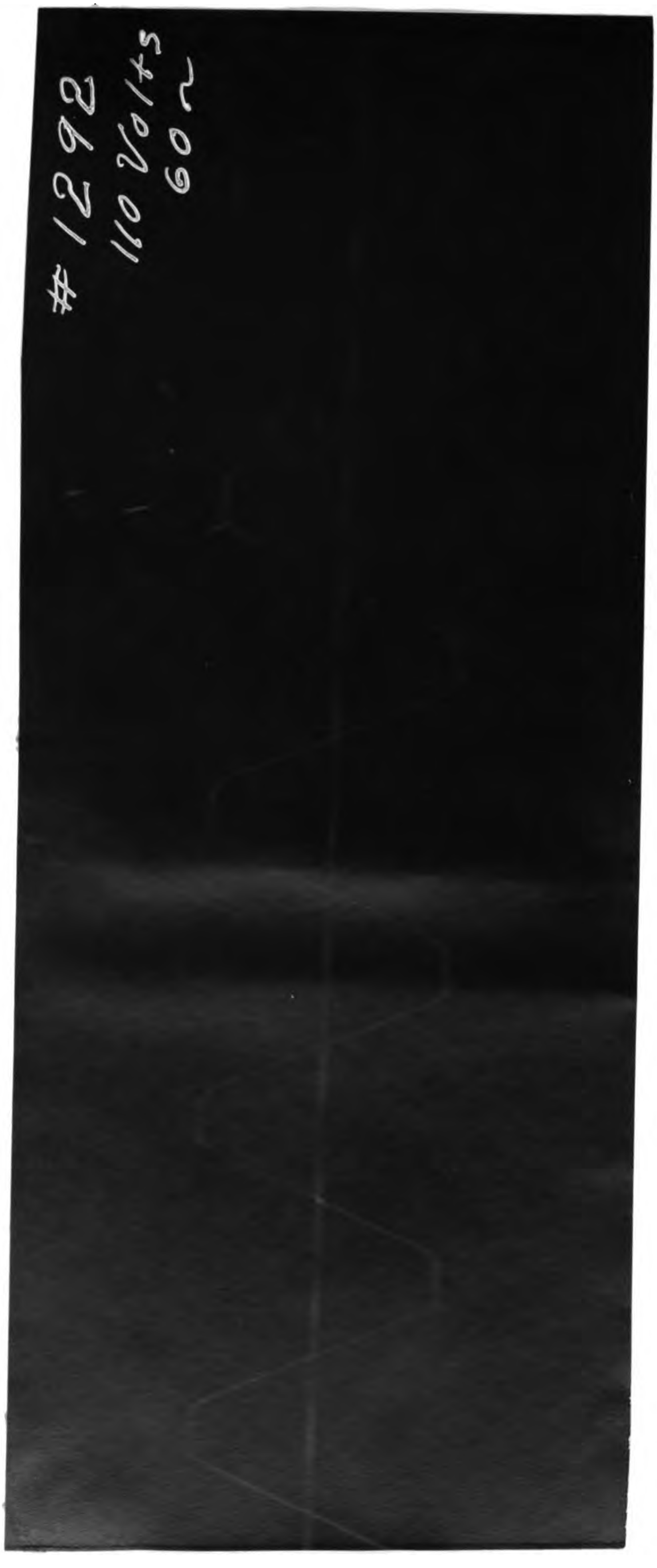
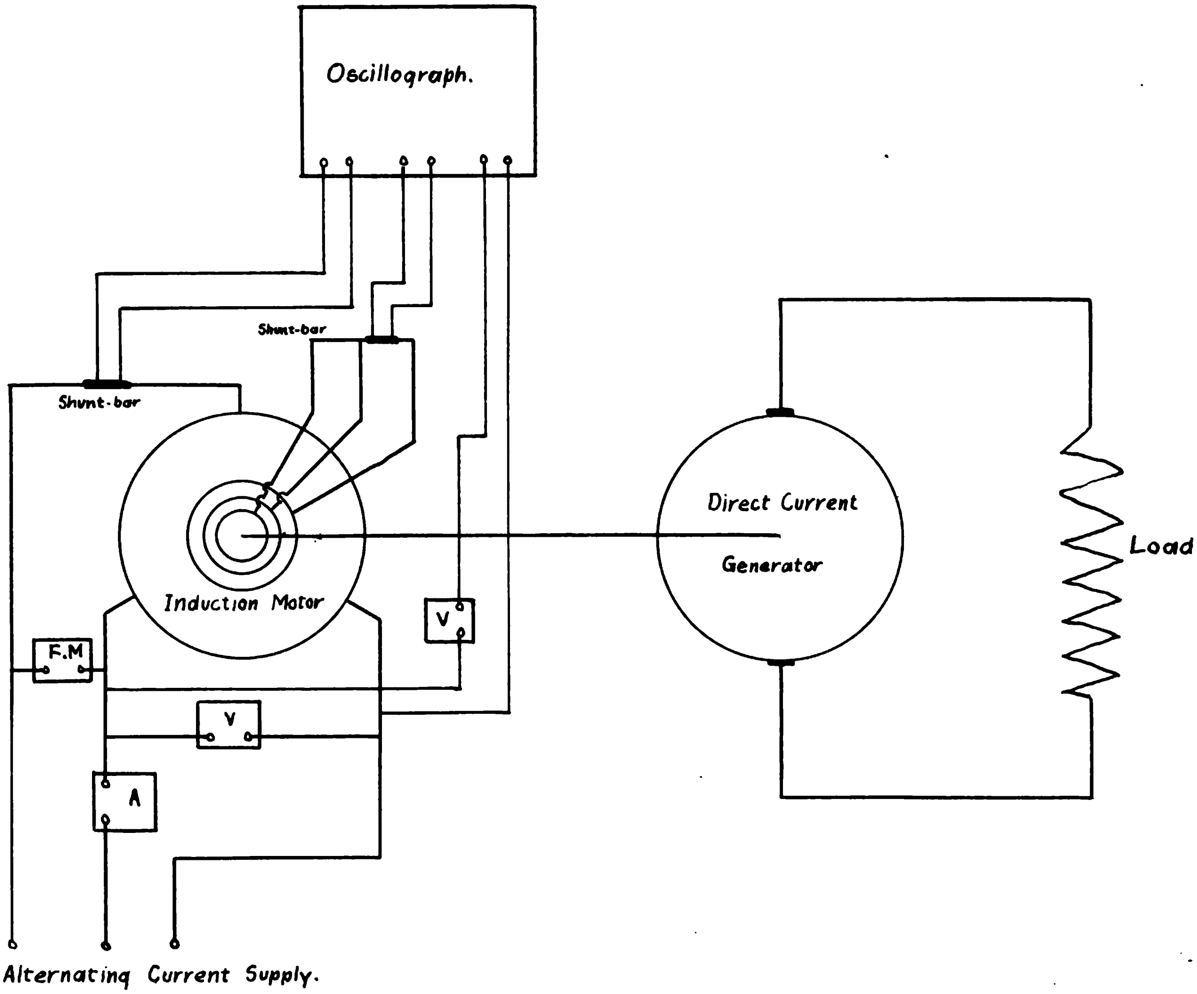


DIAGRAM OF CONNECTIONS.



APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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